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An investment methodology for materials

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Abstract

Will a new material innovation succeed in the market place? Should time and money be invested in developing it? By whom? A methodology has been developed to address these questions. The investment methodology for materials (IMM) is proposed to help identify promising materials innovations at an early stage, helping to direct research and development in directions most likely to lead to successful exploitation, and guiding investment strategy to achieve this. IMM adapts existing and emerging predictive software tools and business strategies to materials innovations, linking them to give a practical, comprehensive procedure. It consists of three interwoven strands: *viability assessment*, *market forecasting* and *value capture*. Viability assessment involves the analysis of technical suitability of the material for an application, an estimate of production cost, and the market's trade-off between performance attributes and cost. Market forecasting involves gathering application-specific market preferences, making an estimate of the technically and economically viable market size, and predicting the timing of industrial adoption by comparison with relevant historical precedents. The analysis of value capture utilises tools to assess industry structure, appropriability and organisational structure. The methodology was developed in response to perceived under-investment in new materials innovation. It has been validated through interviews with venture capitalists and materials industry experts. IMM is aimed in particular at small and medium sized enterprises (SMEs) which are attempting to commercialise a new materials innovation. It is envisioned that IMM will assist SMEs in obtaining financing to commercialise new materials innovations and/or to refocus their efforts. The method is demonstrated through a case study in a companion paper. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Investment methodology; New materials; Viability; Forecasting; Value

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1. Overview of investment methodology for materials (IMM)

Innovations in the materials industry have in the past been considered a high risk investment [1], and have been characterised by long gestation periods between invention and widespread market adoption [2]. For these and other reasons, they have generally been driven by large enterprises [3] and national governments. In this paper, an investment methodology for new materials (IMM) is proposed which could both reduce risk and shorten that gestation time. The risk can be lowered through early viability analysis and the gestation time can be shortened, and thus the present value of expected revenues increased, through earlier and more effective information exchange. This methodology is designed to assist SMEs to commercialise new materials innovations in an industry previously dominated by large enterprise.

IMM assesses the technical and economic viability of

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the materials innovation and also the likelihood that a specific company could capture the value created by adoption of the innovation. Specifically, it is envisioned that IMM should provide a structured, informed procedure for assessing the attractiveness of investing in the scale-up required for commercial production of a new material. IMM can be divided into three segments: *viability*, *market forecasting*, and *value capture* (see Fig. 1). A material is *viable* in an application if the balance between its technical and economic attributes are favourable. Assessing viability involves technical modelling of the application, cost modelling of manufacturing, input from the market assessment, and value analysis. The *market assessment* utilises techniques for identifying promising market applications and for forecasting future production volume. Likelihood of *value capture* is assessed through an analysis of industry structure, organisational structure, intellectual property (IP) issues, appropriability, and the planned market approach. Using the two metrics of size of viable markets and value capture to characterise materials, it is clear that the most desirable investment opportunities lie in the upper right hand quadrant of Fig. 2. The position of a not-yet-commercialised structural material on these two axes is not easy to predict — polyethylene, at the top left, was at first thought to have only a tiny potential market. Control of intellectual property is a key to value capture in the materials industry (as elsewhere), as the positions of Kevlar™ and of Gore-Tex™ indicate. With functional materials, of which light-emitting polymers (LEPs) are an example, the positioning on the figure may be more certain, though still an informed guess.

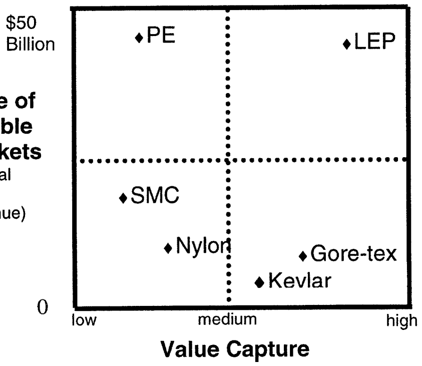

Fig. 2. Market size and value capture as measures of the attractiveness of a materials innovation. Both are discussed in a later section of the paper.

There already exists a substantial body of literature and experience on of the topics listed above, each corresponding to a segment of Fig. 1 and a module of this paper. The novelty of the methodology proposed here lies in their integration into a concurrent procedure. It may be thought that this step is an obvious one, but the history of materials development suggests that the modules (the groupings shown in Fig. 1) are frequently treated in isolation, compromising the effectiveness of the analysis.

2. Viability assessment

The viability of a new material in a given application depends on the balance between its performance, its cost, and its value. There are three steps in evaluating it. The first is the assessment of *technical performance* (Fig. 3, upper left oval). Performance metrics are identified and evaluated for competing solutions for the design [4]. Each application can be modelled in this way in order to provide a basis for performance comparisons between new material solutions and incumbent solutions (Section 2.1).

The second step is the *analysis of cost* (Fig. 3, upper

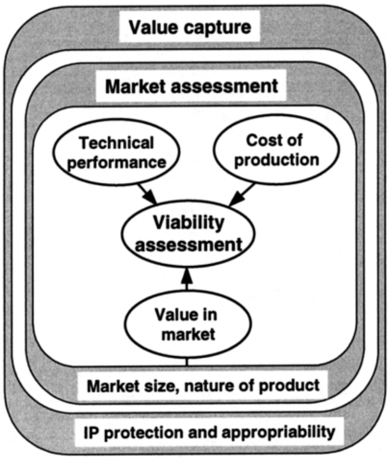

Fig. 1. The steps in implementing the investment methodology for materials (IMM). Each part of the diagram is described in a section of this paper.

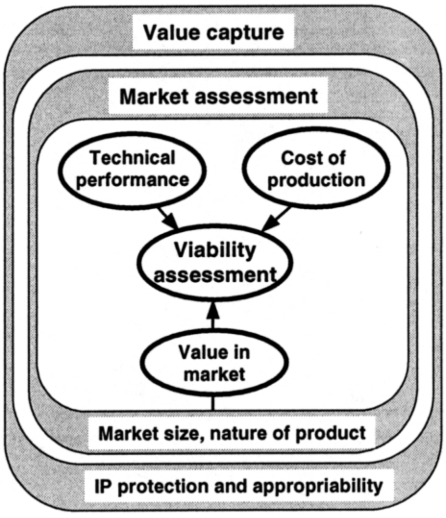

Fig. 3. Overview of viability assessment.

right oval): how much does it cost to achieve a given value of a performance metric? The quantity of material required to meet constraints on stiffness, on strength, on energy absorption, etc., is calculated from straightforward technical models. The cost, C, of producing this quantity of material in the desired shape is the output of the cost model (Section 2.2). The final step is that of *assessing value* (Fig. 3, lower oval): is the change in performance worth the change in cost? Balancing performance against cost and value is an example of multi-objective optimisation. It is discussed in Section 2.3.

2.1. Modelling technical feasibility

Before recommending a new material to a designer, or investing in manufacturing equipment to industrially produce a new material, it is essential that the new material be well understood from a technical perspective. The first module of the analysis (upper left oval of Fig. 3) takes as input the property profile of the new material, allowing its comparison with the profile of existing materials in a range of potential applications. Contemporary software, typified by the Cambridge Engineering Selector (CES [5]), allows the retrieval and comparison of physical, mechanical and thermal properties of thousands of materials. Comparison by function (as well as by simple property), is enabled by using material 'indices' that characterise the performance of a material in a given function. Material and first-order processing costs are also captured, as well as certain environmental information [5,6].

The use of software of this sort, illustrated in Section 2.3, allows the initial, scoping step in establishing technical merit. Almost always this must be supplemented with more detailed analysis, identifying performance metrics, for which we shall use the symbol P, that measures technical excellence and comparing those of the new material with those of existing materials [7] — in a later example, the performance metric is the *energy absorbed per unit volume* in an energy absorbing system. The output of the technical assessment is a tabulation of these metrics for new and incumbent materials. It is worth emphasising that viability does not necessarily require greater technical excellence, since it is the balance between this and cost (to which we now turn) that determines viability.

2.2. Modelling cost

The second step in exploring the technical viability of a materials innovation is that of establishing the primary production and secondary processing costs. Most models to predict manufacturing cost as a function of production volume rely on historical data for existing processes. It is common to approximate costs crudely when the process has not been developed past the pilot scale, the manufacturing method is untried, and the potential for technical advances exist. Such approximate estimates can be useful, but a predictive cost model that allows for sensitivity analysis on technical uncertainties is better. This is made possible by technical-economic cost modelling (TCM) [8].

TCM enables a cost comparison between functionally similar components or systems made with competing materials and processing methods. Developed at the Massachusetts Institute of Technology over the past two decades, TCM has emerged as an accepted metric for material and process comparison for automotive manufacturers and suppliers. TCM can facilitate credible communication with design engineers about new material innovations and enable the development of product cost scenarios that are based on potential technological changes [8–11].

The upper right oval in Fig. 3 represents a technical cost modelling module. The inputs into this module include technical properties of the new material, process information, estimated dimensions and key design features of the desired applications, and desired production volume range. The main output is a comparison between the cost, C, of a part made of a new material and one made of an existing one. Additional outputs are a manufacturing cost estimate over a range of production volumes, cycle time estimates, limiting intermediate variables, costs broken down by accounting line item, and the results of sensitivity and scenario analysis. A detailed application of the method to metal foams can be found in Maine [2].

2.3. Value or 'utility' analysis

If the use of a new material delivers products with better performance at lower cost than existing solutions, the innovation is viable. Barriers to entry may delay the substitution, but, eventually, it will occur. However, it is commonly the case that a new material offers enhanced performance but with higher cost, or is cheaper but with lower performance, than existing solutions. The new material may still have a viable market niche, but, to establish this, more information is needed about how the market values performance. The central oval in Fig. 3 represents a module for exploring trade-offs and assessing value. It utilises the profile of a new material, the economics of production (including scenario forecasting), knowledge of existing products and technologies, and measures of utility for the cost and/or performance attributes of the new material.

Here we have an example of the problem of finding a compromise between two conflicting objectives — that of maximising performance and at the same time of minimising cost. When a design has two or more objectives, solutions rarely exist that optimise all of them simultaneously. The objectives frequently conflict, meaning that any improvement in one is at the loss of another. However, some solutions can be rejected quickly because-in the words of optimisation theory — they are *dominated* by other solutions, meaning that other solutions exist that have better values of both (or all) the performance metrics. The solutions that cannot be rejected in this manner lie on a line called the *non-dominated* or *optimum* trade-off surface [12,13]. (Fig. 4a).

The trade-off surface identifies the subset of solutions that offers the best compromise between the objectives, but it does not distinguish between them. Two strategies are then possible. The simplest is to examine the trade-off surface, using intuition to select one or more non-dominated solutions for further consideration. The alternative — one that requires more information — is to construct a composite objective function or *value function*, V; the solution with the minimum value of V is the overall optimum. This method allows true multi-objective optimisation, but requires more information than the other two. It is explored next.

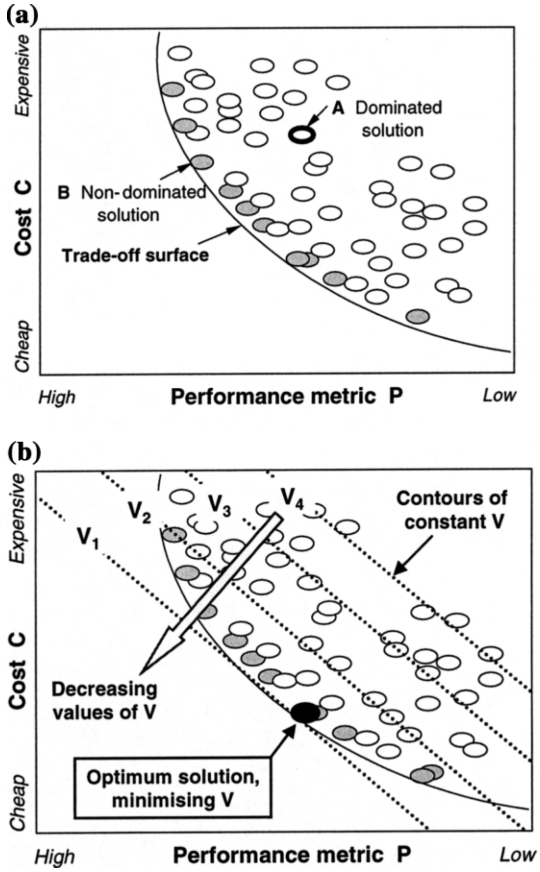

Fig. 4. (a) Dominated (open symbols) and non-dominated solutions (full symbols), and the optimum trade-off surface. (b) Optimising through use of a value function. The optimum choice is that at the point at which the value line is tangent to the trade-off surface.

The value function combines metrics of performance, P_1, P_2, $P_3 \ldots$, (defined in such a way that minima are sought for each) with cost, C, to form an overall objective function, V. Here we make use of a locally linear function, defined by:

$$V = \alpha_1 P_1 + \alpha_2 P_2 + \ldots + C \tag{1}$$

A new material is viable in a given application if, for some range of production volume, it has a lower value, V, than any other material. The α values in Eq. (1) represent ‘utility’ or ‘exchange’ constants, each measuring the change in V for a unit change in P_1, P_2, etc. Their magnitudes depend on the application and the value associated with each performance metric — and this involves information from the market assessment module, described in Section 3. Given values for the α values, contours of V can be plotted on the figure, as shown in Fig. 4b. The optimum choice, co-minimising both performance and cost, is that at which the value contour is tangent to the trade-off surface, since it is this solution that minimises V. Further details of the method can be found in Williams [14].

Consider, as an example, the performance–cost trade-off of materials for a the light, stiff panel. (This example is relevant in many automotive, aerospace, and infrastructure applications.) A cost metric — the cost per unit stiffness — is plotted along the vertical axis and a performance metric — the mass per unit stiffness — is plotted on the horizontal axis. The open ovals show the range of cost and performance offered by conventional materials. The trade-off surface, shown in Fig. 5, is the lower envelope of materials on this plot. Three unconventional materials — aluminium foams, shown in black — lie outside this trade-off surface. It is clear that the foams are attractive candidates for stiffness-limited structures when the value associated with weight savings is high. Dominated solutions (those above and to the right of the trade-off surface on Fig. 5) are uncompetitive on the grounds both of cost and of performance.

All this can be deduced without the use of Eq. (1), and, often, it is enough. But if the exchange constant of Eq. (1) is known (in this case, α is the value associated with weight saving, with units of \$/kg) then the more analytical approach can be used.

3. Market assessment

Science-based innovations require an early market assessment to link the worlds of engineering and finance [14]. Market assessment involves both the technical inputs of performance metrics and the market inputs of customer requirements and emerging opportunities. Desired outputs include: information to direct

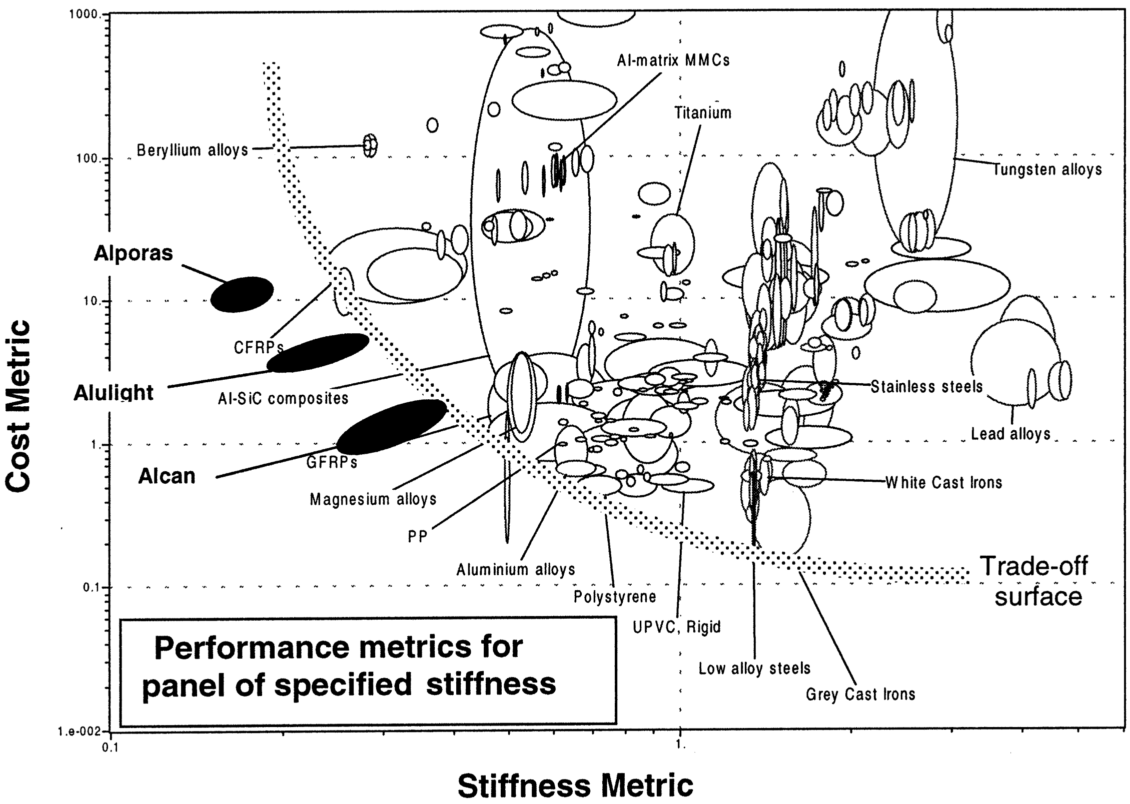

Fig. 5. Performance–cost trade-off example of a light, stiff panel. The full symbols show the position of a material innovation – that of metal foams (Alporas, Alulight and Alcan are the products of three different suppliers).

technical development, such as suitable markets on which to concentrate development, and exchange constants for value analysis; and information to guide business decisions, such as the market segments that offer the greatest promise, sizes of those markets, and anticipated timing and amount of potential revenue flows. These outputs are depicted in Fig. 6. An early market assessment for a new material involves the following two strategies, which we now develop.

Strategy A: the search for *new markets* or *new applications* enabled by the new material. This search is based on performance and relies on satisfying a consumer desire that is not currently met. Examples of the above include the novel processing of PTFE to create Gore-Tex^{TM} offering performance in combined winter/rain/sports/casual jackets; the development of cobalt–samarium magnets that made it possible to design lightweight earphones and compact DC motors; the advances in silicon wafer manufacturing which have contributed to the development of the computer chip industry; and the development of light emitting polymers enabling thin, large area displays. Success here is difficult to achieve but the potential payoff is large.

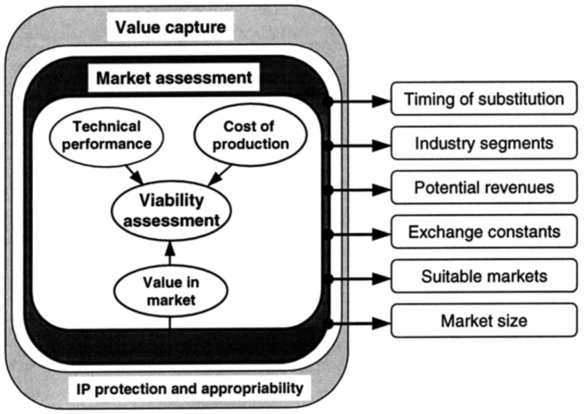

Fig. 6. Market assessment information flow.

Strategy B: the exploration of *substitution* into existing markets. This strategy involves six broad steps, shown in Fig. 7.

1. Potential markets are identified by comparing the properties of the new material with those of existing materials, noting its most promising property combinations, or 'index-values' (for more on this, see Ashby [4]). The established applications of existing commercial materials with similar property profiles are explored as a first estimate of potential markets.
2. The sizes of potential markets for the new material are determined through public information sources (WWW, electronic news search services, etc.).
3. The potential markets are prioritised according to

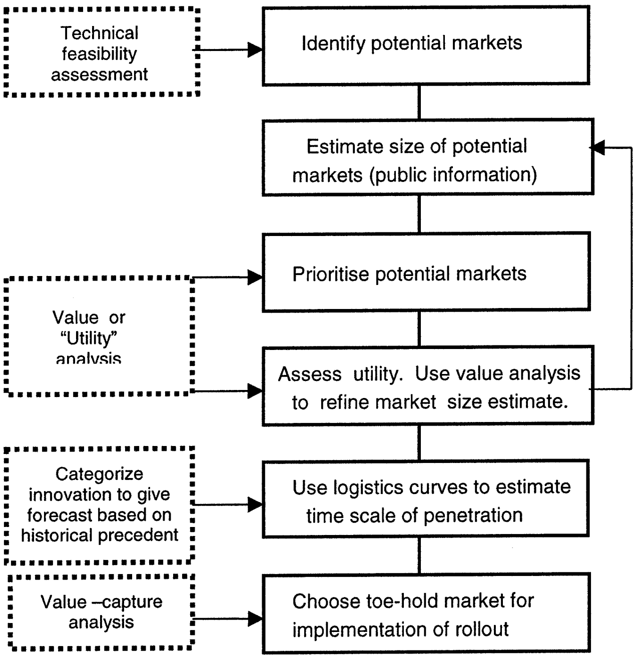

Fig. 7. Steps of market assessment (Strategy B).

market size and estimated type of substitution (Fig. 8). This initial prioritisation step provides input for the technical assessment, cost modelling, and value analysis modules. Market size estimation is an iterative process, with refined estimates becoming possible only after viability analysis is performed.

4. The utility of different markets and/or applications for the performance-cost attributes of the new material is assessed. Utility analysis [15] — a technique for determining the α values of Eq. (1) — is useful both to screen potential applications and as an input into the value function, which enables material selection based on a combination of cost and performance metrics.

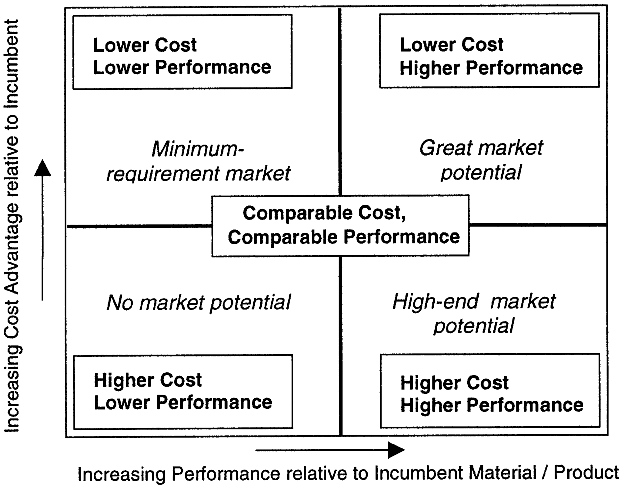

Fig. 8. Performance/cost attributes.

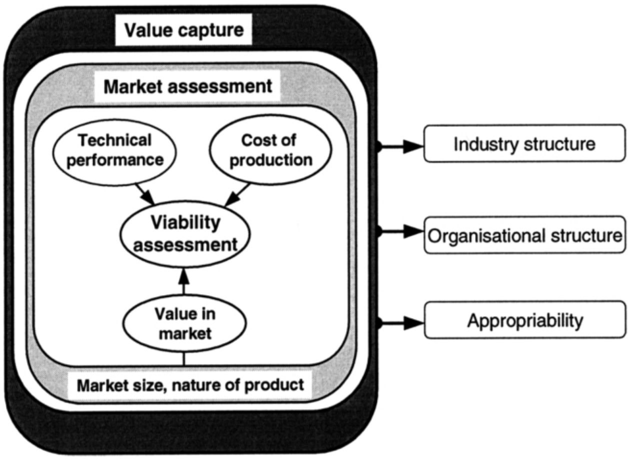

Fig. 9. Overview of value capture analysis.

5. Logistics curves [16] and assessed performance–cost attributes [17,18] are used to estimate penetration into identified markets and applications.
6. An implementation plan is created for the order of markets to be entered, seeking an entry market with minimum risk.

Estimates of market-demand are always uncertain. If the innovation is deemed viable, performance and cost characteristics can help in estimating penetration rates of the material into the targeted markets (Fig. 8). Lower cost/lower performance innovations serve the minimum requirements of customers for the application. For substitution to occur, this lesser functionality must be provided at a reduced cost. Oriented strandboard substituting for plywood in furniture is an example of this type of substitution. An example of technological innovation allowing for performance enhancements but at (initially) higher cost is carbon fibre reinforced plastic boat hulls substituting for wood hulls. If the materials innovation enables entirely new applications, it does not need to be compared with an existing product or technology, but, rather, with assessed customer requirements and safety standards. Each of the four sectors of Fig. 8 is associated with a characteristic market-penetration rate that can be estimated by comparison with historical substitution curves for materials with similar performance and cost characteristics [19].

By following the procedure outlined in Fig. 7, answers to guide further technical and business assessment can be reached. Market assessment is seen here as an interim, but vital, step in reaching an investment decision. The overall goal is to ensure that the assumptions on which market forecasts are based are sound, and to link the technological innovation's characteristics with the market dynamics of the industries in which the applications are targeted.

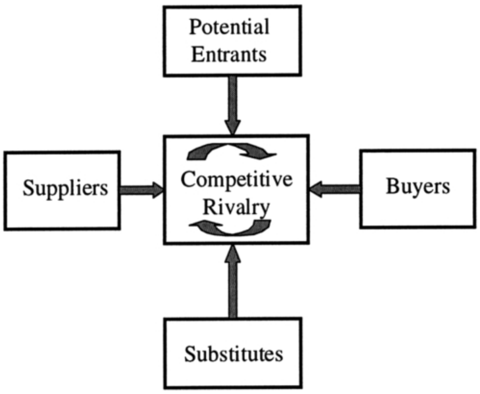

Fig. 10. Porter's five forces as a means of assessing industry attractiveness.

4. Assessment of probability of value capture

Viability assessment and market assessment may demonstrate that the innovation under consideration has the potential to create enormous value, but this alone is not sufficient to guarantee investment. In order to invest, the investor must be convinced that he will be able to capture a significant portion of this value. The concept of *appropriability* — the ability to capture value — is based on an analysis of industry structure, competitive advantage, and organisational structures (Fig. 9). These we now discuss.

4.1. Industry structure

Michael Porter's methodology [20] for assessing *industry attractiveness* provides an inter-industry attractiveness rating, ranging from low to high. Porter assesses the attractiveness, or potential for profitability, of an industry by examining the rivalry of competitors in the industry, supplier power, buyer power, barrier to new entrants to the industry, and the threat of substitute products, as depicted in Fig. 10. Technological innovation can alter the attractiveness of an industry by changing one of these factors, for example, by raising or lowering the barriers to new entrants to the industry. Examples are the innovation of continuous casting that took away the scale advantage of large semi-fabricators with capital-intensive hot mill plants, and that of bubble-jet printing, which changed the competitive position of laser-printing technology. Both innovations brought strong manufacturing cost advantages, and also lowered the barriers to new competitors by lowering the minimum capital investment required to compete. Thus, Porter's methodology can help inform investors whether a selected industry is competitively attractive and whether a technical innovation is likely to increase or diminish this.

4.2. Appropriability of profits

Ownership of intellectual property (IP) is of high importance in extracting value from commercialising a materials innovation. Without patent or trademark protection, it is difficult to maintain a profit margin in mass production of any product. The concept of *Appropriability* was developed [21] to measure the degree of IP protection and the ability of the innovating firm

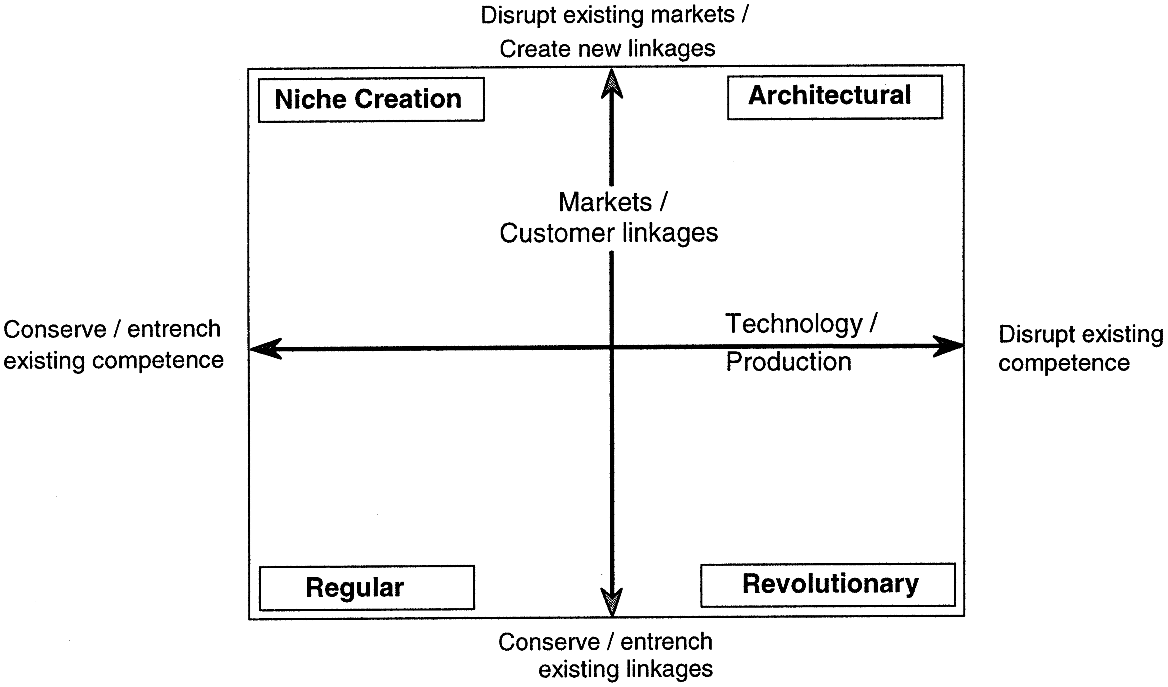

Fig. 11. Abernathy and Clark's transilience map.

to capture the profits from commercialising a new technology.

Teece [20] divides appropriability regimes into *tight*, where strong patent or trade secret protection, asset type, and the type of innovation combine to enable the capturing of innovation profits, and *weak*, where information about the innovation is not well protected and the innovator has difficulty controlling its exploitation. Tight appropriability regimes are very desirable as they allow, at least temporarily, for monopoly conditions.

The assets necessary to manufacture or provide an infrastructure for the innovation influences appropriability by creating barriers to entry and exit. Teece categorises these assets as *generic*, *specialised*, and *co-specialised* [21]. Generic assets are manufacturing, distribution, marketing, or infrastructure assets that are widely available: example are stamping presses for making either steel or aluminium car body panels, and injection moulding equipment that can be used for any thermoplastic. Specialised assets are assets that are not generally available and need to be tailored to the innovation: custom-made capital equipment for manufacturing is an example. Co-specialised assets are assets with bilateral dependence with the innovation diffusion; the innovation of cars powered by natural gas requires a network of natural gas fuelling stations for the innovation to be successful — the stations exist solely because of the vehicles and the vehicles' success is dependent on a re-fuelling infrastructure. Specialised and co-specialised assets act both as barriers to entry for would-be imitators of the innovation and as the cause of potential irreversible commitments which can lock an innovator into a chosen strategy before a dominant design has emerged.

Categorising past innovations can provide a method for selecting relevant historical precedents to help with predicting market substitution and appropriability. Abernathy and Clark [22] classify innovations into one of four quadrants, shown in Fig. 11. *Regular innovation*, found in the bottom left quadrant, refers to incremental technical change that builds on established technical and production competence, retaining existing markets and customer-base. This type of innovation incrementally reduces cost, improves performance or improves reliability, while strengthening existing technological and marketing competencies and linkages. *Revolutionary innovations*, such as transistors replacing vacuum tubes or jet engines replacing reciprocating engines, are innovations that overturn established technical and production competencies, but allow a manufacturer to retain their existing markets and customers. *Niche Creation innovation* is the application of existing technologies to new market applications − waterproof cameras, for instance. Lastly, *Architectural innovation* involves new technology that disrupts existing competencies creating a new product that disrupts existing market and customer linkages; the creation of the radio and the development of the Ford Model T provide examples. Abernathy and Clark use these four types of innovation to mark the extremes of what they term Transilience, defined as 'the capacity of an innovation to influence the established systems of production and marketing' [22].

Categorising a potential materials innovation according to its position on the Transilience Map can help in locating an appropriate historical precedent, guiding market forecast and appropriability comparisons. For more guidance on assessing the appropriability of an innovation, we have developed Table 1. Tightness of appropriability increases to the left-hand side of the table.

4.3. Organisational structure

The most attractive innovation opportunity can be squandered by a company without an effective organisational structure [23]. In the materials industry in particular, organisational competencies are required to interchange knowledge across disciplinary fields, functional roles, organisational boundaries, and the marketplace. Entrepreneurial experience of management, presence of a visionary deal-maker, flexibility of the organisation, effective knowledge acquisition and management, and operational efficiency are all important ingredients for successful innovation.

One of the largest differentiators in organisational structures is the size of the organisation. Small firms generally exhibit a more flexible and opportunistic approach to their decision-making. The financing limitations of small firms make the presence of a 'deal-maker'

Table 1
Appropriability guide

	← Tightening Appropriability Regime			
IP/trade secret protection	High	Medium	Low	None
Specialised assets	High	Medium	Low	None
Co-specialised assets	High	Medium	Low	None
Innovation type	Architectural	Niche product	Revolutionary	Regular
New product cycle time	Slow	Medium	Fast	Continuous
Protectable industry?	High	Medium	Low	No

Table 2
How tasks of innovation strategy are accomplished in large and small firms [25]

Strategic tasks	Large firms	Small firms
Integrating technology with production and marketing	Organisational design Organisational processes for knowledge flow across boundaries	Responsibilities of senior managers
Monitoring and assimilating new technical knowledge	Own R & D and external networks	Trade and technical journals Training and advisory services Consultants Suppliers and customers
Judging the learning benefits of investments in technology	Judgements based on formal criteria and procedures	Judgements based on qualifications and experience of senior managers and staff
Matching strategic style with technological opportunities	Deliberate organisational design	Qualifications of managers and staff

in senior management particularly critical for success. In larger firms in research-intensive industries, a key component of an innovative corporate culture is the resource allocation process. Henderson [24] singles out two models of resource allocation that predominate in successful, innovative pharmaceutical firms. The first revolves around a 'single, highly respected and knowledgeable individual' who was able to make cross-boundary connections acting as the key decision maker. The second successful model is that of a 'relatively high conflict committee' who made resource allocating decisions through 'constructive confrontation across the group' [24].

Evaluating the organisational strengths and weaknesses of a firm cannot be entirely generalised. However, it is possible to use the academic literature on organisational structure to form a checklist of relevant attributes. Tidd et al. [25] propose a list of strategic tasks necessary for organisations to successfully innovate (Table 2) [25]. For small firms wishing to evaluate the innovative capabilities of their organisation, a checklist should include: the level of entrepreneurial experience of management, the presence and competence of a visionary deal-maker, level of demonstrated flexibility of the organisation, mechanisms for effective knowledge acquisition and management, and evidence of operational efficiency.

5. Conclusions and investment strategy

The key go/no go questions of investment in the materials innovation or company can be answered by the three main parts of the methodology of Fig. 1.

1. *Viability*. The viability assessment consists of two predictive models — the first for performance, the second for cost — and a method for examining the trade-off between the two, determining whether customers will judge the product to be good value for money. Only if the material is technically and economically viable is an investment justified, but viability assessment is not enough; the market forecast is also essential.
2. *Market assessment*. Investment is justified only if potential market-size is sufficiently large. The market forecast feeds back into the viability assessment by identifying promising market segments and the value consumers attach to them, and it assesses the size of the market that is likely to adopt the innovation. Historically relevant innovations are utilised to as a basis for the forecast.
3. *Value capture*. Finally, investment is justified only if the likelihood of capturing the value created by the material innovation (after considering potential collaborations) is high. The value capture assessment utilises three established strategy tools: those of industry analysis, appropriability, and organisational assessment. The unique feature of the methodology developed here is the incorporation of this essential component of business analysis into the viability assessment of a material innovation at an early stage.

This methodology also provides some insight into the type of organisation most likely to find investment attractive. Logistics curves can help in estimating the length of payback on an initial investment. In the case of long-term payback, a public organisation or a very large corporation may be the only interested investors. Conversely, the case of a staged investment with a 5-year payback, the potential of a buyout, and large 'upside' profit, appears an attractive one to venture capitalists.

Given the decision to invest, market approach is the key to managing cash flow. A new material can first be exploited in small volume high value-added applications (such as sports equipment) to gain credibility, and brand name recognition, and to provide initial cash flow. Smaller companies can gain from joint ventures with suppliers, customers, and distribution channels, since such collaborations provide financing opportunities, faster market penetration, and a more detailed understanding of the market.

In summary, the attractiveness of a materials innovation can be determined by systematically assessing the technical and economic viability, along with the likelihood to capture profits created. This methodology may help match new materials innovations to market opportunities more quickly and may prevent some companies from pursuing investment strategies destined for failure. This methodology is illustrated through a case study of the competition between several processes for one new materials innovation: that of aluminium foams, in an accompanying paper [26].

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